training. The training facilities would be used to verify pre-flight analyses. The primary mode of training would be computer based. No motion base, fixed based, or flight aircraft facilities will be required.

Advanced Development Tasks Required

The selected technology/advanced development tasks that will enhance the next generation space launch system include tasks applicable to all architectures and tasks unique to an architecture. The generic tasks include: (1) avionics systems that can be upgraded, software that is automatically generated and validated, and the health management of in-flight functions; (2) electro-mechanical/hydraulic actuators and their electrical power driving and switching systems must be matured, with emphasis on the power supply systems; (3) advanced manufacturing to demonstrate and validate the most effective construction techniques for the expended cryo-propellant tanks (automatic welding and statistical process control (SPC) of components will reduce inspection, with significant reduction in cost and facilities without compromising reliability); (4) nontoxic orbital maneuvering subsystem/ reaction control system propellant systems will increase the operational flexibility and decrease the associated costs by elimination of hazardous systems and the associated control of risks; and (5) a low-cost cryogenic upper stage engine, the number-one priority of the Space Transportation Advisory Committee, is required for all architectures. Modification to the existing Centaur and implementing an RL–10C engine, results in rapid development time and low program risk. A single-engine Centaur decreases costs, increases reliability, and increases operability. Application of advanced technology to the low-cost 50k-pound class engine also increases the capability of architectures.

The architecture-unique technology tasks include reusable propulsion/avionics modules (Architecture 2A') to substantially reduce launch costs. Propulsion/avionics modules package the costliest vehicle elements (main engines, auxiliary subsystem's power elements, main propulsion feedline elements, auxiliary propulsion subsystem, the thrust structure, and vehicle flight avionics systems) to be recovered in a dry condition and with minimum refurbishment. Hybrid motors (Architecture 2C) offer increased safety, low cost, operational flexibility, and an environmentally "friendly" propulsion. The technology effort is to mature and demonstrate hybrid propulsion technology to provide an adequate technology base and U.S. manufacturing infrastructure for U S. commercial expendable launch vehicle competitiveness. A low-cost hydrogen fuel booster engine (Architectures 2B and 2C) using term-advanced technologies will have low development costs, rapid development time, and low program risk. The continuation of the space transportation main engine is required to retain the capability to transition to Option 2 in 2002.

Costs

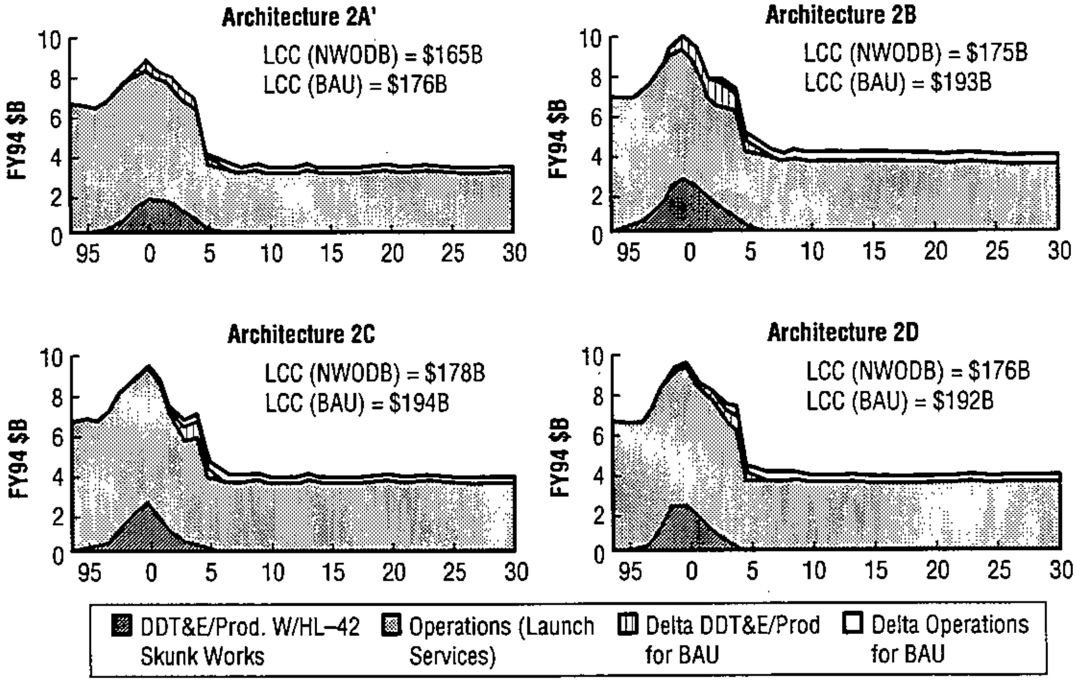
Design, development, test, and evaluation, production, and operations costs have been estimated over the life of the program. All transportation costs that are required to launch NASA and Department of Defense payloads over the 1994 through 2030 time period have been included, with the exceptions noted in the ground rules listed below. Although new and innovative ways of doing business, compared to the traditional ways NASA programs have been managed in the past, have been identified, their cost impact has not been fully qualified or validated. The development of the HL–42 and the CLV–P could use a "Skunk Works" type approach. This approach has been used successfully in major military programs such as the Hercules, U–2, and SR–71. In a study conducted on the HL–20 payload system by the Langley Research Center and Lockheed, it was determined that significant savings could be achieved using this approach. Based on those results, the new approach for the HL–42/ CLV–P could yield reductions as high as 40–45 percent in the total spacecraft development and production cost estimates, compared to the traditional "business-as-usual" estimates.

These costing ground rules were followed:

- All costs are included with the following exceptions:
  - Civil service salaries and travel, and research operations support (ROS)
  - Pre-planned product improvement after the year 2000
  - Commercial flights.
- Business as usual and new ways of doing business are included. The latter is characterized by:
  - "Skunk Works" development for HL–42 and CLV–P (firm requirements, single management authority, small technical staff, customers on site, contractor inspections, limited outside access, timely funding, reports only important work, simple drawing release, rapid prototyping, etc.).
- Launch services are purchased from commercial suppliers (eliminated program office PMS and ETB overheads, and reduced operations cost by 10 percent).
- Architectures 2A', 2C, and 2D assume reduced Space Station *Freedom* return cargo. Architecture 2B is full return.
- Costs assume use of single-engine Centaur for upper stage, Titan IV shroud, and European Automated Transfer Vehicle.
- Cost estimates include reserves (30 percent of design, development, test, and evaluation, 20 percent of production), fee (10 percent), and program support (20 percent) except for production estimates based on actual current hardware production costs (i.e., external tank modules, Centaur upper stage, shrouds, and Automated Transfer Vehicle).
- Expendable launch vehicle infrastructure cost adjustments are Department of Defense estimates assuming 50 percent common, 25 percent Titan-unique, 12.5 percent Delta-unique and 12.5 percent Atlas-unique.
- Unreliability costs for all vehicles except the Space Transportation System, are based on actual experience on existing expendable launch vehicles and projected reliabilities for new vehicles. Payload losses ($10k per pound) and reflight costs are included with HL–42 and CLV–P losses calculated for one vehicle each.
- Launch vehicle design, development, test, and evaluation costs are spread over 4 years using 60 percent cost/50 percent time Beta distribution. HL–42 and CLV–P are spread over 6 years.
- Production costs are spread over 3 years using 30 percent/40 percent/30 percent.
- Pre-development costs of 7 percent design, development, test, and evaluation are allocated at one percent for Phase A and six percent for Phase B.

The most cost-effective operations approach is for NASA to purchase commercial launch services similar to the current Delta and Atlas. This enables a healthy competitive environment with foreign suppliers and places payloads in orbit at the lowest cost. This approach would also reduce the government cost associated with project support, supporting the program office, providing a support contractor base, and maintaining the NASA facilities required to support the system over an extended operational period. Ten percent cost reduction in ground processing and mission operations can be realized by the purchase of launch services.

Figure 23 shows the design, development, test, and evaluation and operations cost profile over the 1994 to 2030 time period for Architectures 2A', 2B, 2C, and 2D. The cost estimates include the total government resources required to meet the planned NASA and Department of Defense mission models. The costs are plotted to show both the "business-as-usual" (BAU) estimates and a "new ways of doing business" (NWDB) estimate. In the latter, preliminary savings attributed to the "Skunk Works" type development and to the purchase of launch services are identified.



BAU = Business as usual
NWODB = New ways of doing business

Figure 23.—Total mission model cost spread.

Assessment

Option 2 satisfies all national launch needs including commercial, national security, and civil missions. In addition, crew safety is improved by safe aborts for all mission phases, the elimination of solid rocket boosters, and reducing exposure from 8 to 3 flights per year. On uncrewed flights, mission reliabilities of greater than 0.98 are achievable. The Option 2 architectures significantly reduce life-cycle costs. For modest investments of $7B–$13B, annual operating costs can be reduced from $6.7B (current) to $3.7B–$4.0B, resulting in total life-cycle cost savings of approximately $50B. The architectures reduce technical and programmatic risk below prior programs by utilizing major elements/systems derived from current technology, large performance margins, evolution of existing propulsion systems, and management practices that minimize requirements change/growth. Environmental impacts are improved by the elimination of solids (except for small booster separation motors) and the elimination of hypergols (except for single-engine Centaur roll control).

The Option 2 architectures enhance the commercial competitiveness of launch vehicles by utilizing launch vehicle services if the new ways of doing business are adopted and providing competent capabilities in all payload ranges. Industrial capability is maintained and enhanced through near-term development efforts that can be phased to allow steady capability requirements (evolution path is 20k-cargo launch vehicle-crew transport launch vehicle). In comparison to existing systems, Option 2 offers other distinct advantages such as performance and reliability increases, operability increases, autonomous flight control, and growth capability to meet next generation space missions.

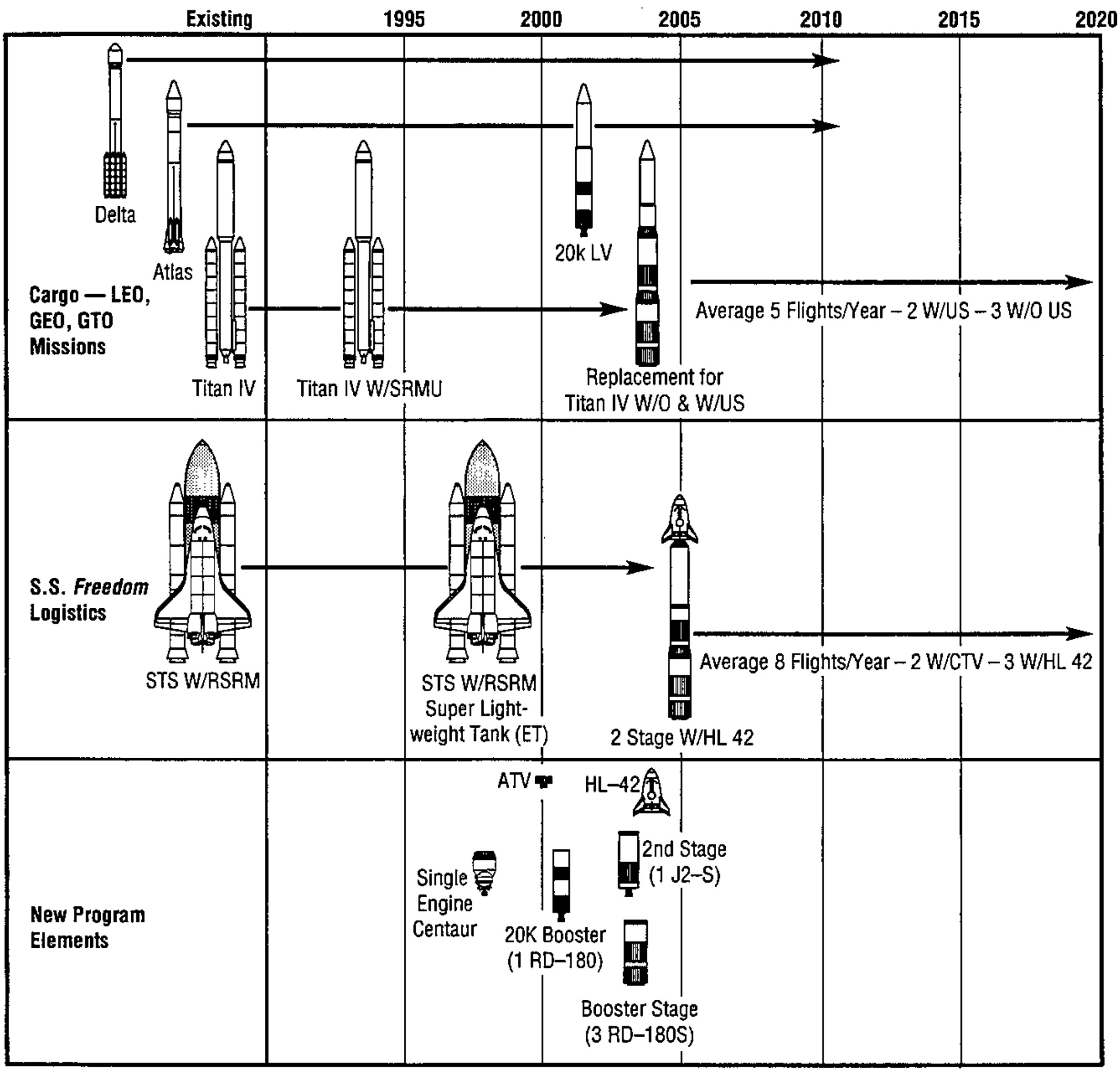


FIGURE 24.—Access to Space—Option 2D: Architecture 2D.

At the end of the study, a selection was made of alternative Architecture 2D as the most attractive overall. It is illustrated in figure 24, and its costs are shown in figure 25.

Findings and Recommendations

Major findings include:

- Significant cost reductions, increased reliability, and increased crew safety can be accomplished relative to current systems.
- Operations cost reductions can be achieved with new designs, improved technology, and streamlined programmatics (architecture effects are second order).

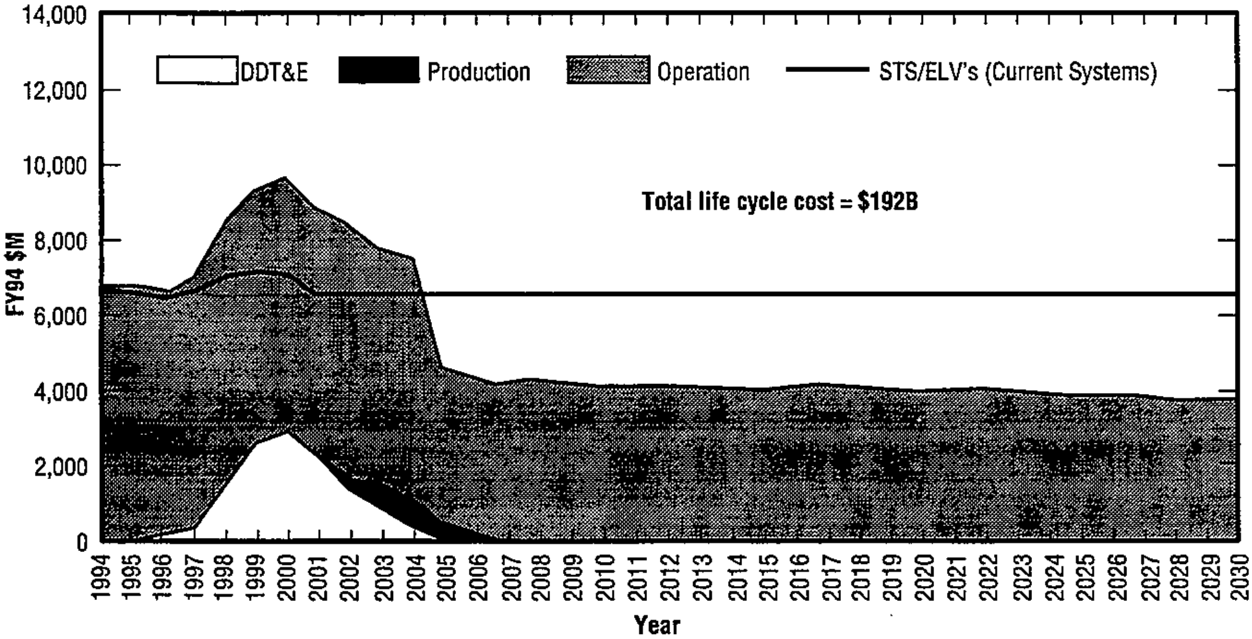


FIGURE 25.—Total mission model cost spread (Option 2D—BAU).

- $40–$50B life cycle cost savings require a $7.5–$13B investment for design, development, test, and evaluation.
- Life-cycle cost does not discriminate between architectures (eight percent variation).
- For Titan/Shuttle-class payloads, Architecture 2A' is the lowest cost; Architecture 2D is the lowest cost for 20k-class payloads.
- Propulsion system development time is a schedule driver.
- Increased performance capability relative to current systems allows for future growth in national launch requirements without compromising cost reductions.

In summary, the Option 2 recommendations are:

- The Space Station design should include the capability to accept crew/cargo from expendable launch vehicles.
- In order to improve crew safety, do not expose the crew to launch risk purely for cargo delivery and provide safe abort/escape for all ascent phases.
- In order to reduce cost, introduce conventional technology and reduce the complexity of existing systems, automate ground and flight systems for operability and reliability, implement second generation PLS with minimum crew flight rate, and utilize single low-cost commercial system to launch all Titan and Shuttle-class payloads.
- Develop an effective strategy to incrementally implement the next generation launch system with a range of capabilities, select an architecture where the propulsion elements lead the vehicle elements, consider ATV as the cargo transfer element, and support an aggressive technology/advanced development set of tasks until the next generation of systems for access to space are defined.
- Architecture 2D is the recommended architecture. Its costs are the lowest for the Atlas replacement vehicle, and it uses an existing engine to minimize research and development risk.

Option 3 Team Analysis

Approach

A joint NASA and Department of Defense team was assembled to develop a well-rounded approach to identifying the nation's space transportation architecture requirements and implementation alternatives. Vehicle concepts were designed for robust operational margins, instead of performance capability, through the use of various advanced technologies. However, a "culture change" in launch vehicle development, certification, and operations management must accompany the use of advanced technologies to leverage them to the greatest extent possible. Relevant government and industry concepts, operations models, and management philosophies were reviewed and considered by the team in its analysis.

Architectural Alternatives Analyzed

On the basis of the 1990 Modified Civil Needs Data Base, approximately 90 percent of all future low-Earth orbit payloads are under 20k pounds and are under 20 feet in length. Delivery of these payloads (and their geosynchronous Earth orbit equivalent) was a primary driver in determining the payload size requirement of the advanced technology vehicle. There are approximately 18 satellite delivery missions in the 10k- to 20k-pound class each year (low-Earth orbit equivalent). A new liquid oxygen (lox)/liquid hydrogen (LH_2) upper stage, approximately one-third the size of the Centaur, will be required to transfer the largest payloads from low-Earth orbit to geosynchronous-Earth orbit. The new vehicle is also required to support satellite servicing missions at a rate of approximately one every 3 years. An option for delivering Titan IV-class payloads was evaluated and vehicle concepts were developed to deliver a 45k-pound payload to low-Earth orbit. However, this was not baselined due to the small number of Titan-class flights per year (three), the uncertainty of their payload volume requirements post-2000, and because of the corresponding increase in vehicle size. Instead, such a vehicle is treated as an option.

A total of 150k pounds of Space Station resupply logistics are required to be delivered, and 125k pounds to be returned, by the vehicle each year, based on current requirements for Space Station permanently crewed capability. The Space Station payloads are transported using standard unpressurized logistics carriers and the minipressurized logistics module.

Based upon previous flight experience and state-of-the-art avionics, the Option 3 vehicle must be capable of autonomous flight operations. When required (e.g., servicing missions), the vehicle has the capability of being operated on-orbit by a two-person crew to enhance safety and perform nonstandard mission operations. Also, the vehicle must have the capability to transport an additional four Space Station crew members and the associated payloads that require late or early access.

Taking all domestic payload requirements into consideration, the advanced technology vehicle is configured with a 25,000 pound payload capability to a 220 nautical mile circular orbit inclined at 51.6 degrees. To meet this mission model, 39 flights per year, on average, will be required. The vehicle has a payload bay that is 15 feet in diameter and 30-feet long. An expendable launch vehicle of the Titan IV class will be used to meet the missions requiring a 40,000 to 50,000 pound payload capability. However, an option has been developed that uses a larger advanced technology vehicle to meet the all the requirements.

Space Transportation Architecture

Figure 26 illustrates the recommended Option 3 architecture based on the mission requirements from section 2.1. The 30- and 45-foot payload bay vehicles are shown as alternatives A and B. Cargo and crewed missions are shown along with requirements for major new elements and the approximate time frame of their implementation. This architecture is generic, with the reusable launch vehicle icon shown in the figure representing several advanced technology launch system concepts evaluated.

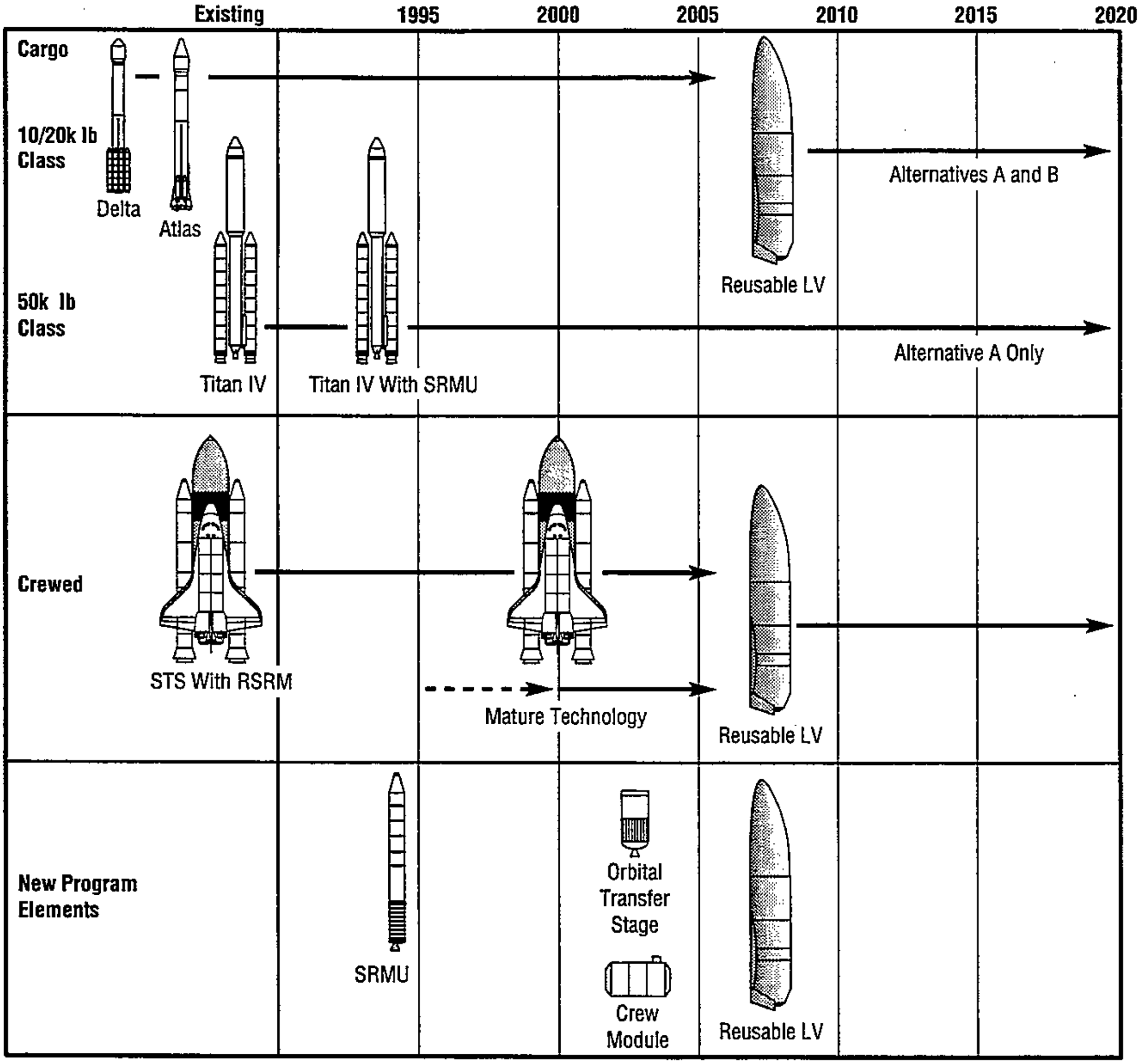


FIGURE 26.—Option 3 architecture.

Vehicle Concept Options

Three launch vehicle concept design options have been chosen by the Option 3 team for engineering analysis and costing, as representative of the numerous fully-reusable vehicle concept possibilities. The concepts are:

- An all-rocket-powered single-stage-to-orbit (SSTO–R)
- A combination of air-breather plus rocket-powered single-stage-to-orbit (SSTO–A/R)
- A combination of air-breather plus rocket-powered two-stage-to-orbit (TSTO–A/R).

These three concepts have been identified because they represent the largest range of candidate vehicle options in terms of technology requirements for reusable launch systems, and because government studies were already in progress to evaluate these concepts at the initiation of this study. It is emphasized that these concepts are intended to serve as representative vehicles for technology and operations evaluations, and are not intended to serve as final concept recommendations. The use of advanced technologies is being considered to increase operability, margins, durability, and to enable full reusability.

Major Features of Architectures

The three reference vehicle concepts were designed to an equivalent depth so that an "apples-to-apples" comparison could be made. They all had features that would enhance reliability, operability, and maintainability. These features include the following:

- One-time vehicle flight certification.
  - This requires building in increased margins over that used in the Space Shuttle design.
  - The Space Shuttle is essentially recertified after each flight.
  - The tests and inspections required for this greatly increase the ground processing time.
- Off-line payload processing.
  - To minimize the impact of the payload on the vehicle, it is required that the payload be processed separately from the vehicle and that the payload place minimum requirements on the vehicle.
  - The payload bay of the Space Shuttle is reconfigured for each flight, which again increases the ground processing time.
- Minimize serial processing.
  - To reduce the overall ground processing time, serial processes must be minimized.
- Durable thermal protection system.
  - Many programs are underway, e.g., at Langley Research Center and Ames Research Center, to develop a thermal protection system that is both more durable than the current thermal protection system used by the Space Shuttle and also requires less servicing between missions.
- Autonomous avionics.
  - The use of the Global Positioning System, coupled with the advances in electronics, makes this feasible using today's technology.

Table 1 compares the key features of each vehicle.

TABLE 1.—*Reference vehicle comparisons*

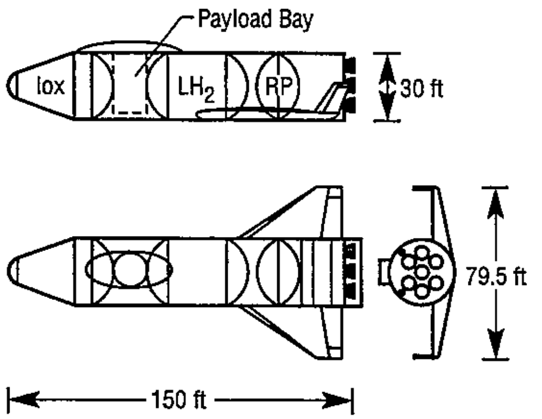
Feature	SSTO (R)	SSTO (A/R)	TSTO (A/R) (Booster)	TSTO (A/R) (Orbiter)
Gross Mass (lb)	1,961,303	917,000	352,000	450,000
Dry Mass (lb)	159,500	239,000	252,000	52,000
Engine Type	RD–704 Class	Low-Speed Airbreather/ Ramjet/Scramjet & Linear Modular Aerospike Rocket	Turbofans/ Ramjets	P&W RL–200 (New Engine Development)
Lox Tank	Al/Li Integral/Circular	Al/Li Integral/Conformal	N/A	Al/Li Non-Integral
LH_2 Tank	Al/Li Integral/Circular	N/A	Graphite Composite Integral	Graphite Composite Integral
Slush Hydrogen Tank	N/A	Graphite Composite Integral/Conformal	N/A	N/A
Primary Structure	Graphite Composite	Graphite Composite	Graphite Composite	Graphite Composite
TPS	Passive AFRSI/TABI/ACC	Passive FRCI–12/TABI/ Carbon-SiC Active LH_2	Passive TABI/TUFI	Passive TABI/TUFI
Aerosurface Controls	EMA	8,000 psia Hydraulics	8,000 psia Hydraulics	EMA
Aerosurfaces	ACC	TMC (With C/SIC Where Needed)	Ti H/C	ACC
Electrical Power Generation	Fuel Cells	Fuel Cells	Air Turbine	Fuel Cells

Single-Stage-to-Orbit—All Rocket

The design philosophy of the reference single-stage-to-orbit all-rocket vehicle is to maximize the lessons learned from the Space Shuttle program and apply the minimum technology required to allow for an operationally efficient vehicle. These major design requirements, in addition to the characteristics identified previously, include the following:

- Eliminate downrange abort sites
- Eliminate hydraulics
- Eliminate hypergolic propellants
- Use evolutionary engines
- Use Al-Li for the LH_2 and lox tanks
- Use normal boiling point propellants
- Use simple circular cross-section fuselage and tanks
- Design propellant tanks for internal pressures similar to the Shuttle external tank.

The all-rocket-powered single-stage-to-orbit configuration is designed to take off vertically, like a standard launch vehicle, and land horizontally at mission completion, like the Space Shuttle. Two suboptions exist within this rocket option: (1) a vehicle based on seven lox/LH_2 engines evolved from the space shuttle main engine with equivalent performance characteristics, but designed for higher levels of operability and maintainability; and (2) a vehicle based on seven tripropellant (lox/RP/ LH_2) engines of the performance class of a single bell Russian RD–701 (i.e., RD–704). The RD–701 has component heritage from the RD–170 (Zenit and Energia booster engine) and RD–120 engines. The RD–701 drawings are 80 percent complete. This latter tripropellant option is illustrated in figure 27.



Payload*	Final Orbit
25k lb	Station: 220 nmi circ at 51.6°

*Includes payload and ASE

Vehicle:

GLOW:	1.96 Mlb
Dry Mass:	159.5 klb
Propellant Mass:	1.74 Mlb
Propellant Type:	Lox/LH_2/RP
Main Engine Type/No.:	RD–704/7
Vac Thrust (ea.) Mode 1/2:	441.4/175.5 klb
Vac ISP Mode 1/2:	407/452
Area Ratio:	74:1
OMS Engine Type/No.:	New Lox/LH_2
Vac Thrust (ea.):	6 klbf
Vac Isp:	462 s
Area Ratio:	100:1
Cryo Tanks	Al-Li
Primary Structure:	Gr-Composite
Control Surfaces:	ACC
TPS:	ACC/TABI/AFRSI
Payload Bay—Usable Volume	15 ft D × 30 ft L

Notes:
- Vertical takeoff/horizontal landing
- 15 percent dry weight margin
- Option for carrying two on-orbit operations crew for 7 days
- Option for carrying four S.S. *Freedom* rotation crew in payload bay
- Option for carrying high energy transfer stage for Atlas class (5k lb) GEO missions

Figure 27.—Reference single-stage-to-orbit rocket.

In addition, after initial and preliminary discussions with the U.S. Air Force Space Command, it was determined that a 45-foot long cargo bay coupled with a 45k-pound payload capability to low-Earth orbit at the 28.5 degree inclination may allow the advanced technology vehicle to deliver the next generation of Titan IV payloads (scheduled to undergo a block change early in the next century). Because of the requirement for a third propellant tank (i.e., RP), the tripropellant option allows for a 15-foot diameter by 45-foot long cargo bay to be placed longitudinally in the vehicle.

The masses associated with the lox hydrogen and the tripropellant vehicle variants are shown in table 2, and the cost estimates in table 3.

TABLE 2.—*Vehicle masses*

	Lox/LH_2	Tripropellant: 30-ft Bay
Dry Mass	233k lb	159k lb
Gross Mass	2.48M lb	1.96M lb

The weights of these vehicles can be reduced substantially by adopting graphite composites for the fuel tanks instead of aluminum-lithium. This is discussed under the Single-Stage-to-Orbit Feasibility section.

TABLE 3.—*Cost estimates for the single-stage-to-orbit rocket*

FY94 $B	Lox/LH_2	Tripropellant: 30-ft Bay
Technology	0.90	0.90
DDT&E	17.60	16.70
Annual Operations*	1.40	1.40

* SSTO Vehicle and Associated Elements Only

Single-Stage-to-Orbit—Air-Breather/Rocket Combination

Air-breathing/rocket-powered, single-stage-to-orbit, horizontal takeoff and landing (HTOL) aerospace planes are highly integrated systems with unprecedented levels of interdisciplinary interactions involving a broad spectrum of technologies. This type of vehicle has numerous design variables and can evolve to a robust, flexible machine using a highly optimized design process if the systems/disciplines are integrated synergistically and the appropriate technologies matured. Such a vehicle can provide routine access to orbit at reduced cost, increased operational flexibility (ground and flight), and reliability. Many of these attributes stem from the airplane characteristics of this vehicle, such as lifting body, air-breathing propulsion, horizontal takeoff and landing, and so forth. The single-stage-to-orbit air-breather/rocket combination is an airplane that goes into orbit and, as such, can be expected to accrue many of the desirable operational characteristics associated with contemporary high-performance aircraft. Specifically, they materialize through:

- Gradual step and check engine startup and shutdown
- Horizontal takeoff/abort capability
- Atmospheric abort with powered fly back
- Large launch window potential
- Launch offset capability
- Large cross range
- Subsonic and/or supersonic ferry capability with either SLH_2 or LH_2
- Hypersonic cruise capability.